Miller, Wendy F., Bell, John M., & Crompton, Glenn
(2014)
The impact of Cool Roof applications on energy performance : results from Australian sub-tropical and tropical field studies. In
Proceedings of World Sustainable Buildings Conference (SB14), CIB - International Council for Research and Innovation in Building and Construction, Barcelona.

The Impact of Cool Roof Applications on Energy Performance: Results from Australian Sub-tropical and Tropical Field Studies

Abstract: *Cool roof coatings are identified by their solar reflectance index. They have been reported to have multiple benefits, the extent of which are strongly dependent on the peculiarities of the local climate, building stock and electricity network.*

This paper presents measured and simulated data from residential, educational and commercial buildings involved in recent field trials in Australia. The purpose of the field trials was to evaluate the impact of such coatings on electricity demand and load and to assess their potential application to improve comfort whilst avoiding the need for air conditioners. Measured reductions in temperature, power (kW) and energy (kWh) were used to develop a predictive model that correlates ambient temperature distribution profiles, building demand reduction profiles and electricity network peak demand times. Combined with simulated data, the study indicates the types of buildings that could be targeted in Demand Management programs for the mutual benefit of electricity networks and building occupants.

Keywords: Cool Roof, demand management, peak load, solar reflectance index, tropical, load shifting

Introduction

A ‘cool roof’ is defined as a roof that, because of its optical and infra-red properties, usually imparted by special coatings, remains at or near ambient temperature under sunny conditions. These special roof coatings are identified by their solar reflectance and thermal emittance. A combination of these two factors is used to calculate a surface’s solar reflectance index. These characteristics, combined with the thermal resistance and thermal transmittance of the roof structure, and internal and external temperatures, in essence are the key determinants of the energy balance of a roof (Figure 1) which in turn impacts on ceiling heat flux and the energy load of internal spaces [1-4] .

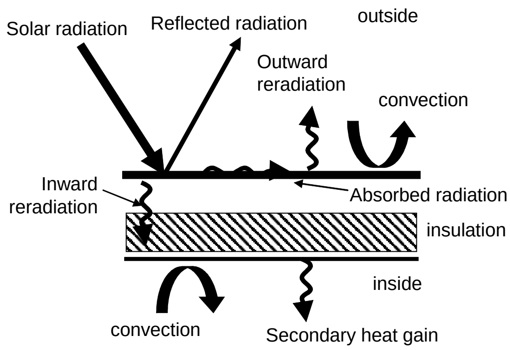

Figure 1 Energy balance of a roof (Source [1])

Previous research on the energy (kWh) and power (kW) savings and load shifting potential of cool roofs has shown that the extent of energy reductions depends on the specific climate and building typology, and that such coatings can also improve cooling equipment efficiency as well as the internal and urban environment [4-8].

The purpose of this research was to quantify the energy, power and comfort impacts of cool roof coatings on a range of building types on ten sites in tropical Townsville (latitude 19.25°S) and sub-tropical Brisbane (latitude 27.5°S) in Australia.

Methodology

The field studies, conducted between 2012 – 2014, adopted a 'before and after' test protocol for fifteen residential, education and commercial buildings, as shown in Table 1.

Table 1 Field Study Building Specifications

#	Brief description, location and usage times	Building and Energy System Characteristics
A	School – conditioned library (1), conditioned assembly hall (1), conditioned classrooms (4 in 2 buildings), unconditioned classrooms (8 in 4 buildings) Brisbane 08:00 – 17:00 week days (M-F)	Mixture of concrete block buildings and light-weight timber buildings. Older classrooms with aged red roof and minimal ceiling insulation. Mix of refrigerative AC types, including multiple split-systems in single conditioned spaces
B1 B2	School - dining hall (1) 05:30 – 19:00 weekdays; 06:30 – 19:00 weekends School - administration building (1) 08:30 – 16:30 week days (M-F) Peak tariff (07:00 – 21:00 M-F) three times the cost of off-peak tariff. Townsville	(B1) Floor area 390m^2; sandwich panel roof; high level of wood framed single glazing; multiple ACs in single conditioned space (B2) Floor area 460m^2; timber framed, light weight, off ground "Queenslander" house converted into offices, most with own independent AC unit.
C	University office building (1) – three storey 09:00 – 17:00 week days (M-F)	Total floor area 3,649m^2. Concrete and breeze block construction, metal roof. District cooling system (chilled water)
D	Retail store: single storey warehouse style building with two tenancies (1occupied, 1 vacant), Brisbane 08:00 – 18:00 seven days/week	Floor area 1250m^2; flat roof Roof mounted air conditioners (96kW ducted unit per tenancy)
E	Airport terminal Brisbane Note: no Cool Roof coating applied	Floor area 55,000m^2. Light color metal roof with 200mm bulk insulation. Multiple chillers with chilled water distribution
F	Housing: single level detached (2) Townsville F1 predominantly unoccupied M-F 8am-5pm F2 predominantly occupied	Both houses on cement slab; metal roof; multiple 'single room' ACs; ceiling fans F1 conditioned area 135m^2; building efficiency - cooling load 101MJ/m^2/yr F2 conditioned area 98m^2; building efficiency - cooling load130MJ/m^2/yr

Temperature sensors (Maxim iButtons) were mounted on a shaded external location, on the roof surface, roof cavity and internal spaces. They were programmed to record temperature every 30 minutes within an accuracy of +/- 0.5°C, to provide daily temperature profiles for each building. Standard revenue meters were installed at the school sites (cases A, B), and a Dent Elite Pro XC data logger at the retail store (case D), to record half hourly electricity consumption for air conditioning loads. The BMS systems of the office and airport terminal (cases C, E) were used to monitor cooling loads (chilled water). Data from an onsite weather station and PV system at Case C was also used. Additional data was secured from local weather stations (Australian Bureau of Meteorology) and historical records (e.g. building documents, electricity bills and energy audits) where such information existed. Thermal simulations were conducted for both of the residences (case F), using BersPro 4.2, accredited software under the Nationwide House Energy Rating Scheme (www.nathers.gov.au). IES VE was used for thermal simulations of industrial and commercial spaces. Most buildings were coated with a Cool Roof product with a solar reflectance of 89%, the exceptions being F2 (solar reflectance 79%) and E (no coating applied). A data analysis tool (using Excel) was developed to correlate temperature and energy data. Historical weather data was used to develop daily ambient temperature profiles for each month, allowing filtering by building specific operational hours, periods of peak demand or tariff times.

Results: Impact on Temperature

Temperatures of the roof surface, roof cavity and non-conditioned internal space were recorded in all buildings (except airport) before and after the application of the cool roof coating. In the retail store, for example, the average roof surface temperature during business hours for the monitored period reduced 9°C post coating (Figure 2). A similar reduction in internal temperature (in the vacant store) was measured. As the AC heat exchanger is roof mounted, the reduction in roof surface temperature equates to an approximate 9% increase in cooling capacity for this type of air conditioner (roof mounted ducted three phase packaged air conditioners) as well as a reduced cooling load (from reduced internal temperature).

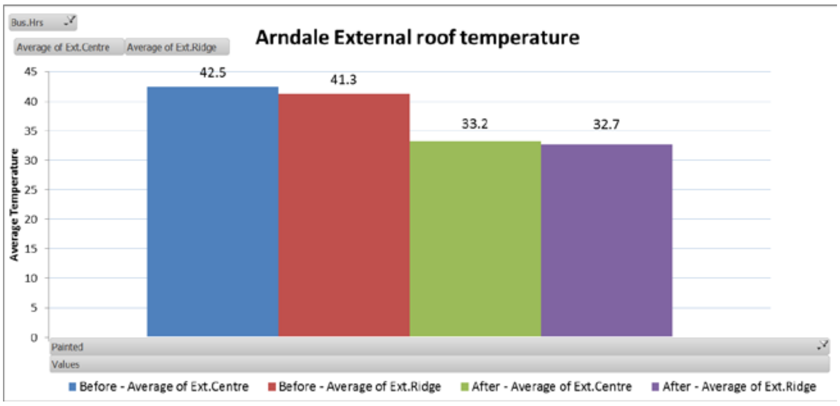

Figure 2 Reduction in roof surface temperature in retail store (Case D)

Reductions in roof surface temperatures are even more dramatic when the data is also filtered for high solar radiation days. This was done, for example, by applying photovoltaic system output data from case C to the temperature data for nearby case B school dining hall (Figure 3). As expected in a southern hemisphere tropical location, temperature reductions were greater on the western roof than on the eastern roof.

Roof cavity temperatures in the school administration building (case B2) on a hot day (34°C), prior to coating, were approximately 16°C higher than ambient, compared with post coating temperatures 2-3°C higher than ambient. This is significant because high roof cavity temperatures reduce the effectiveness of ceiling insulation. The thermal resistance of bulk insulation materials on the Australian market is tested for an ambient temperature of 24°C and for temperature differentials of 18, 12 and 6K. In an air conditioned building, the temperature difference between the internal room and the roof cavity during summer may be well over 20K. Increased temperature differences lead to increased convective currents through the insulation, further reducing their resistance to heat transfer [9].

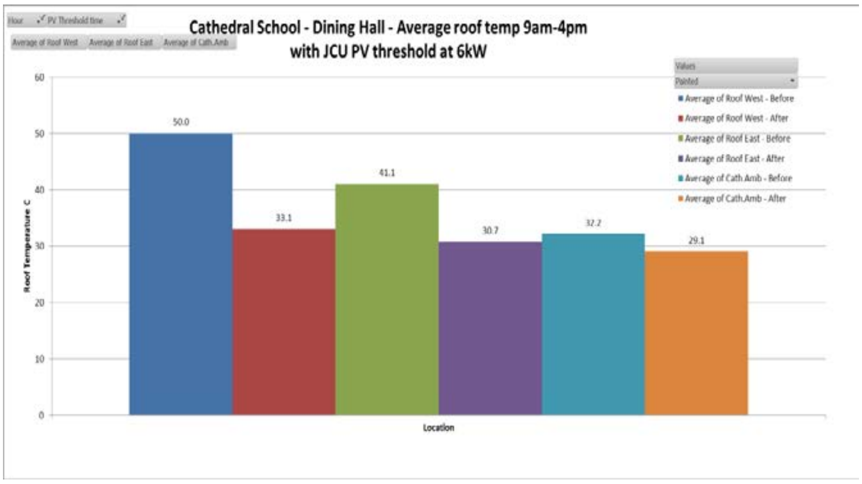

Figure 3 Reduction in roof surface temperature on high solar radiation days

In the non-conditioned classrooms, the internal temperature was monitored to quantify the impact on comfort levels in the teaching spaces (Figure 4). These results are significant as the application of roof coatings may give schools a cheaper option for improving teaching and learning spaces, compared with the installation and operational costs of air conditioners.

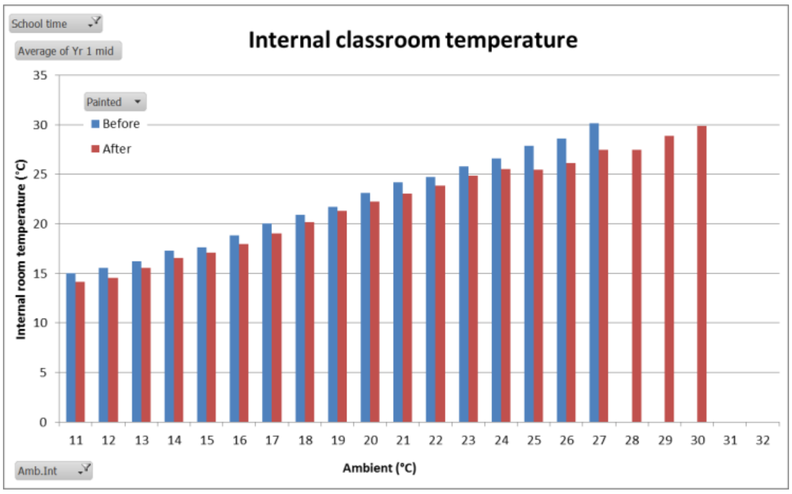

Figure 4 Reduction in classroom temperatures post roof coating

Results: Impact on Energy and Power

Cooling demand was then correlated to ambient temperature, as shown in Figure 5. All buildings showed a similar trend of great demand reductions as ambient temperature increased. Monthly temperature distributions were developed for each building (Figure 6), then applied to the building's cooling energy profile, to establish a weighted average demand for the month (kWh). The 98th percentile monthly temperature value was used to determine the monthly peak demand (kW). Before and after averages are multipled by the number of operating hours per month to arrive at the expected kWh or kW per degree of ambient temperature. Annual reductions could then be calculated (Table 2).

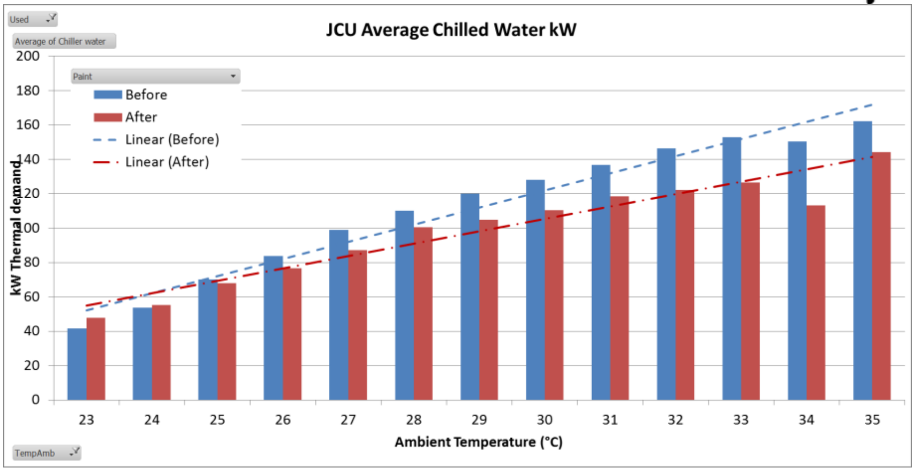

Figure 5 Trend in demand reduction by ambient temperature - office building (Case C)

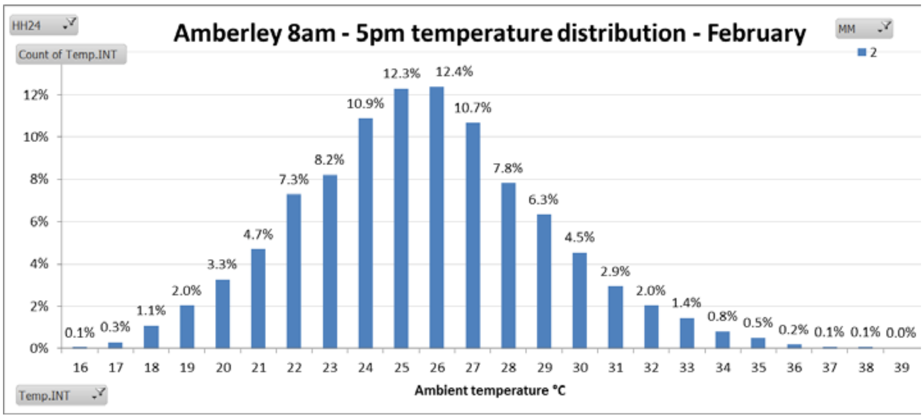

Figure 6 February temperature distribution for school hours

Table 2 Power and energy reductions measured in Townsville

Location	Building type	Reduction in cooling energy (kWh/m^2/yr)	Reduction in peak demand (W/m^2)
Townsville	School Dining Hall	4.95	2.8
	School Admin Building	23.00	9.1
	Office Building	27.00	9.0

Discussion

The broader implications of the field study results were explored through simulation and modelling. Building simulation of one of the houses was used to show the impact that an improvement in SRI would have on the percentage of annual hours the roof cavity would be over 30°C and hence impact on the effectiveness of insulation. The current practice of installing minimal levels of insulation on the ceiling results in 35% of the year with roof cavity temperatures exceeding 36°C, compared with an ambient temperature that excedes 30°C only 2% of the year (Table 3). This suggests that cool roof coatings could play a critical role in the retrofit of existing buildings, as re-coating the roof may be easier and cheaper than retrofitting reflective foil insulation, and it offers other benefits (e.g. roof restoration).

Table 3 Impact of SRI on roof cavity temperature

Changes to roof reflectivity and insulation levels			Roof cavity T <10°C	Roof cavity T 10 – 19°C	Roof cavity T 20 - 30°C	Roof cavity T 31 - 36°C	Roof cavity T >36°C
Ceiling insulation	Under roof insulation	Roof Reflectance	% of year the roof cavity temperature is in each temperature band				
Outdoor ambient temperature			1	15	82	2	0
R2.5	Nil	50%	2	19	44	10	25
R2.5	Nil	90%	2	20	70	7	0

Changes to electricity tariffs may also be an incentive to consider cool roofs as an energy efficiency option. For example, the main operational hours of schools (cases A, B) occur during peak tariff times, so reducing their overall kWh/m^2 usage on hot sunny days would have significant financial benefits. Australia's housing stock is also notoriously energy inefficient [10], and the Queensland government's proposal to move residential customers to time of use tariffs in the near future may act as a catalyst for customer-driven renovations for energy efficiency. Simulations of thirty-seven construction variables (representing common construction types in Townsville) showed that the greatest demand reduction occured when a high SRI (90%) was applied to housing with dark and medium coloured roofs and houses with low levels of insulation. A simple equation was used for economic modelling, taking into account the cost difference between standard paints and cool roof coatings; the savings from reduced demand; the life expectancy of the coating and annual increases in the cost of electricity (10%). Combined with the data from the non-residential buildings, suggests that the electricity network could target owners of specifc building types (Table 4).

Table 4 Characteristics of buildings suitable for Cool Roof Demand Management

Broad category	Specific characteristics
Spatial dimensions	High roof area to internal volume ratio
Roof reflectance	SRI less than 70
Insulation	Ceiling insulation <R3; and/or no reflective foil
Cooling system	Conventional refrigerative AC systems (not district cooling); Roof mounted air intake; High AC use (number of hours / days of year / low set point)
Electricity Tariff	Buildings with high daytime time of use tariffs and/or high demand charges

The Demand Management potential of Cool Roofs could be further explored through extension of the data analysis model developed for these field trials. More extensive data is required to enable proportional aggregation to predict customer demand response for varying times and conditions. The specific data needed includes (a) accurate local historical weather data (and arguably predicted future weather data); (b) accurate cooling load profiles for different building types within the network; and (c) regional building construction data and demographics. If this data becomes available for defined areas of interest within an electricity network, modelling would become an important factor in network demand forecasting. The different motivations of participants and the electricity networks (Table 5) would also need to be considered, to design programs with mutual benefit.

Table 5 Participant motivations for Cool Roof applications

Participant	Motivation / Need
Airport (Case E)	Roof needs recoating for maintenance. Can the cost difference between standard and cool roof coatings be recovered through reduced cooling demand. (Initial analysis revealed an unknown overnight cooling load that needs to be addressed first.)
Schools & Retail (Cases A,B,D)	Predominantly day time operation (high solar radiation). Want to reduce kW or kWh (depends on tariff structure) or avoid need for AC
Office (Case C)	Invested in a very efficient district cooling system. Whilst cool roof coatings can marginally reduce demand, better financial savings can be achieved by altering the times when water is chilled.
Electricity network	Fundamental conflict between their revenue model (sell as many kWh as possible) with their need to manage infrastructure expenditure (restrain peak kW).

Conclusion

This field study adds evidence to the body of research, reinforcing the temperature and energy benefits provided by cool roof coatings in these subtropical and tropical regions. It has demonstrated the successful application of a flexible model for the evaluation of these benefits, but points to the need for more specific building and network data, and acknowledgement of participant motivations, before broader network-scale demand management programs can be developed.

References

1. Parker, D. and S. Barkaszi, *Roof solar reflectance and cooling energy use: field research results from Florida.* Energy and Buildings, 1997. **25**(2): p. 105-115.
2. Bell, J.M., G.B. Smith, and R. Lehman. *Advanced Roof Coatings: Materials and Their Applications*. in *CIB 2003 International Conference on Smart and Sustainable Built Environment*. 2003. Brisbane.
3. Gentle, A., J. Aguilar, and G. Smith, *Optimized cool roofs: integrating albedo and thermal emittance with R-value.* Solar Energy Materials and Solar Cells, 2011. **95**(12): p. 3207-3215.
4. Levinson, R., H. Akbari, and J. Reilly, *Cooler tile-roofed buildings with near-infrared-reflective non-white coatings.* Building and Environment, 2007. **42**: p. 2591-2605.
5. Synnefa, A., M. Saliari, and M. Santamouris, *Experimental and numerical assessment of the impact of increased roof reflectance on a school building in Athens.* Energy and Buildings, 2012 **55**: p. 7-15.
6. Pisello, A.L., M. Santamouris, and F. Cotana, *Active cool roof effect: impact of cool roofs on cooling system efficiency.* Advances in Building Energy Research, 2013. **7**(2): p. 209-221.
7. Bozonnet, E., M. Doya, and F. Allard, *Cool roofs impact on building thermal response: A French case study.* Energy and Buildings, 2011. **43**: p. 3006-3012.
8. Santamouris, M., *Cooling the cities - A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments.* Solar Energy, 2014(103): p. 682-703.
9. Su, B. and R. Aynsley, *A Case Study of Roof Thermal Performance in Naturally Ventilated Houses in Hot-Humid Climates under Summer Conditions.* Architectural Science Review, 2006. **49**(4): p. 399-407.
10. Miller, W., L. Buys, and J. Bell, *Performance evaluation of eight contemporary passive solar homes in subtropical Australia.* Building and Environment, 2012. **56**: p. 57-68.